Climate induced changes in the circulation and dispersal patterns of the fluvial sources during late Quaternary in the middle Bengal Fan

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From a transact along 15°N latitude in the middle Bengal Fan, temporal and spatial variations in the granulometric parameters and clay minerals in ^{14}C dated box cores from the eastern, the central and the western regions were studied to determine climate induced changes in the hydrography. Clay assemblages have spatial and temporal changes and are markedly different in the eastern and the western bay. From a high abundance of the clay smectite, which has its major source in the Deccan Basalt in peninsular India, it is inferred that the western bay is predominantly a depocenter of 'peninsular sources'. The eastern and the central regions of the bay, however, mostly receive sediments of the 'Himalayan source'. Related to unstable climate, the reported dominant illite–chlorite (I + C) assemblage in the eastern region of the bay (I + C > 60% smectite < 15%), between 18 and 12.6 ka BP, points to a predominant supply from the Himalayan sources through equatorwards dispersal by the winter hydrography. Higher smectite, and reduced clays of the Himalayan sources (smectite > 25%; I + C > 45%) are reported also after 12.5 ka BP from the eastern bay. These are interpreted as evidences of an intensified SW monsoon and associated change in the dispersal pattern by stronger summer monsoon hydrography which supports across bay dispersal by anticyclonic gyre. The influence of climate on hydrographic changes is consistent during the short events of arid climate (weak NE monsoon) in Holocene in core 31/1(western bay), in which the enhanced contents of the clays of the Himalayan sources are observed (smectite < 40% I + C > 50%). These findings have implications for climate regulated influence of fluvial processes over the areas, hitherto, considered unaffected by the Indian peninsular fluvial sources.

1. Introduction

The Bay of Bengal is one of the largest terrigenous input sites of the world oceans. It receives, through fluvial influx, a large amount of land-released matter from the north (the Rivers Ganga–Brahmaputra), the west (the Mahanadi, the Godavari, the Krishna and the Cauvery Rivers) and the east (the Irrawady River), which contributes towards the growth of the Bengal Fan – the largest of its kind in the world (Van der Borch et al 1974). The Bengal Fan extends for 3000 km N–S and 1430 km E–W at 15° N. Several valleys mark the surface of the fan in the central region of the bay, but presently only one is connected to 'Swatch of no ground' (Emmel and Curray 1984). The annual sediment discharge to the bay is about 2000 million ton from these prominent perennial rivers. Associated with the injection of fresh waters, the peak input of terrigenous flux into the bay, derived from the time series trap experiments, particularly from the Ganga–Brahmaputra rivers (G–B; Ittekkot et al 1991), is during the SW monsoon. Due to the large fluvial influx, there is a
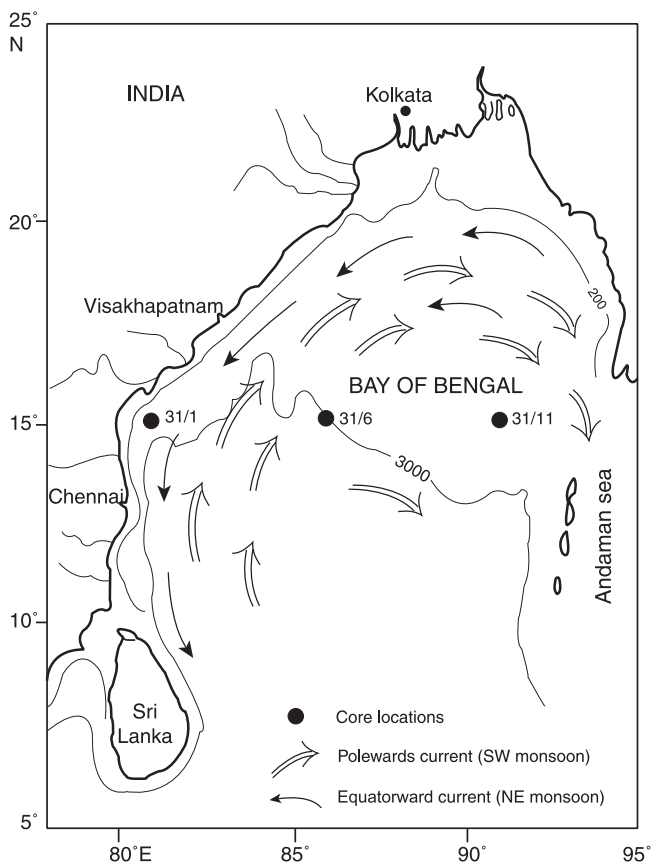
Figure 1. Prevalent regional hydrography (Shetye *et al* 1991, 1993; Verkey *et al* 1996) and core locations in the Bay of Bengal.

significant salinity reduction ($\sim 7\text{‰}$) in the northern bay (Levitius *et al* 1994). The plume of fresh water extends southwards up to $15°$ N latitude.

The bay has a complex hydrography governed by the reversal of winds associated with the monsoon phenomenon. The coastal circulation in the bay is mostly driven by the river runoff and hydrometeorological parameters (Varkey *et al* 1996). Regional, anticyclonic, poleward currents carry high salinity waters of the southern and the central regions across the bay during the southwest (SW) monsoon (June through September). There is also localized upwelling along the east coast of India during the SW monsoon. The current direction changes drastically over the pre- and post-monsoon periods with localized cells. Remotely controlled equatorwards, cyclonic gyre has been reported in the bay during the northeast (NE) winter monsoon (Varkey *et al* 1996). The currents are generally weak, equatorwards during most of the transitional period along the east coast of India (Shetye *et al* 1991, 1993; figure 1). It has been debated whether the intensity of the SW and the NE monsoons is interlinked, i.e., a stronger SW monsoon (summer monsoon) may lead to a weaker NE monsoon (Sarkar *et al* 1990). Based on the isotopic

signature, however, Tiwari *et al* (2005), suggested a weak SW monsoon even though the NE monsoon was stronger during the late LGM. It implies that being climate dependent, the hydrography *vis-à-vis* dispersal pathways of the specific fluvial discharge may also have modified under different climate regimes of weak (stronger) NE (SW) monsoon.

Based upon the studies of the clays and the components of surficial sediments, fluvial sources predominantly contributing sediments into the different regions of the bay have been broadly determined (Kolla and Rao 1991). Because Tiwari *et al* (2005) have shown stronger equatorward currents during the late LGM, when the SW monsoon was weak, which implies that the hydrography of the bay varies with respect to NE and SW monsoons, studies of the surficial sediments alone are not entirely sufficient to understand the source to sink mechanism of specific fluvial sources *vis-à-vis* climatic variability. The climate of the bay is known to have undergone century scale changes since LGM (Chauhan *et al* 1993, 2004; Weber *et al* 1997; Chauhan and Suneethi 2001; Kudrass *et al* 2001; Chauhan 2003). However, studies of temporal variations in the supply of terrigenous clays, under specific influence of climate *vis-à-vis* dispersal pathways of the sediments of these fluvial sources in the different regions of the bay are still in a state of infancy.

The clay minerals are $< 2\,\mu$m in size and have the potential to remain in suspension for long distances in the open ocean. The clay assemblages, being dependent upon hinterland geology, drainage and climate, are also source specific. Being carried mostly in the suspension, the clay minerals have the potential to be used to determine the dispersal pathways of a specific fluvial source. This study evaluates temporal variations in clay minerals and granulometric parameters in two ^{14}C dated cores retrieved from the middle fan region of the Bay of Bengal located in the area which predominantly receives sediments from the peninsular and the Himalayan rivers. Being one of the largest depocenters of terrigenous influx, most of the area of the bay is covered with a fan having altered sequence. In such a dynamic environment, due to the practical problem of obtaining a turbidity free core, and in the absence of availability of any other suitable turbidity free core, we have also used the published results of the clay analysis of Chauhan *et al* (2004) from the eastern region of the bay:

- to obtain a regional clay distribution in the middle fan region and
- to determine specifically dispersal pathways during the LGM, the period not covered by the other cores, for comparison with that of the Holocene. Emphasis is placed to understand the relation

Table 1. *Ages of the cores 31/1 and 31/6 (Chauhan et al 2001).*

Sl. no.	Laboratory no.	Sample interval (cm)	^{14}C age	Corrected ^{14}C age
	Core 31/1			
1	KL 31/1 01	6–8	920 + 90	520
2	KL 31/1 02	18–20	1420 + 90	1020
3	KL 31/1 03	28–30	1720 + 90	1320
4	KL 31/1 04	38–40	2150 + 110	1750
5	KL 31/1 05	46–48	2650 + 100	2250
6	KL 31/1 06	58–60	2900 + 90	2500
7	KL 31/1 07	68–70	3550 + 110	3150
8	KL 31/1 08	74–76	4100 + 110	3700
9	KL 31/1 09	82–84	4200 + 100	3800
10	KL 31/1 10	88–90	4800 + 110	4400
11	KL 31/1 11	118–120	5600 + 120	5200
12	KL 31/1 12	148–150	6000 + 110	5600
13	KL 31/1 13	158–160	6200 + 100	5800
14	KL 31/1 14	168–170	6400 + 110	6000
15	KL 31/1 15	178–180	6790 + 110	6390
16	KL 31/1 16	200–202	7700 + 110	7300
17	KL 31/1 17	213–215	8550 + 110	8150
18	KL 31/1 18	230–232	9230 + 120	8830
19	KL 31/1 19	250–252	9500 + 140	9100
20	KL 31/1 20	268–270	9700 + 120	9300
21	KL 31/1 21	298–300	11400 + 160	11000
	Core 31/6			
22	KL 31/6 1	20–25	2560 + 100	2160
23	KL 31/6 2	40–45	4630 + 150	4230
24	KL 31/6 3	50–55	5260 + 130	4860
25	KL 31/6 4	60–65	6200 + 150	5800
26	KL/31/6 5	85–90	6500 + 130	6100
27	KL/31/6 6	115–120	6450 + 130	6065
28	KL 31/6 7	185–190	6400 + 130	6000

between the climate-induced changes in the hydrography and dispersal pathways of the fluvial clay influx under varied climatic conditions during the LGM (dominant NE monsoon) and the Holocene (intensified summer monsoon regime; Chauhan 2003; Chauhan and Suneethi 2001; Kudrass *et al* 2001).

Because the bay is a depocenter of multiple fluvial systems, core locations have to be chosen in the regions known to have influences of a specific source. For this purpose, the region across 15° N latitude is suitable because:

• in the eastern region, sea surface salinity (SSS) is influenced by fluvial influx of the G–B, while
• the western bay is a depocenter of major Indian peninsular rivers, the Godavari and the Krishna (G–K). Score of cores was collected during the 31st expedition of ORV *Sagar Kanya* from this region. Core 31/1(western core) lies off the

mouths of the peninsular rivers (15.00° 20″ N; 81.49″ E water depth 2524 m), in the regions reported to receive sediments from the peninsular region (Kolla and Rao 1991). The other core (31/6) is located in the central regions (14.59° 68″ N; 86.59 17″ E water depth 2952 m) in the channel–levees system, and is chosen to determine the evidences and consistency of across bay dispersal, or lateral advection of sediments from the channels–levees to the eastern or to the western bay. Because of the non-availability of any suitable turbidity free core from the eastern bay (strongly influenced by the influx of the Himalayan rivers G–B), for comparison of clay abundance with that of the western and the central regions of the bay, we have referred to the published century scale climate reconstruction and clay minerals and granulometric data of Chauhan *et al* (2004) (location 15.00°. 52″ N; 91.10″ E water depth 2713 m) to

arrive at regional changes in the dispersal pathways of the clays from the peninsular and the Himalayan sources.

2. Methodology

The cores were subsampled at 2 and 5 cm (for core 31/6) intervals. Salt free, oven dried, samples were subjected to the granulometric studies at 1φ intervals following the methods of Folk (1966). The clay mineral analyses were undertaken on the oriented, carbonate and organic carbon free, $< 2\,\mu\text{m}$ fractions. Clay minerals have been identified and quantified from the methods of Biscaye (1965). Based upon the replicate analysis the accuracy of the analysis is $\pm 5\%$ for illite, chlorite and kaolinite and $\pm 8\%$ for smectite. The cores have been bulk ^{14}C dated (28 levels, table 1; Chauhan *et al* 2001). In the absence of the apparent age of the waters of the bay, the carbonate ^{14}C dates have been corrected by 400 y to nullify the reservoir effects (Stuiver and Reimer 1993) (table 1). Because these ages are correlated with that of Chauhan *et al* (2004), these are not converted into calendar ages in order to maintain uniformity.

3. Results

The texture of the sediments in cores is presented in figures 2(a)–3(a). The sediments in general, have a silty-clay to clayey-silt texture except in the core 31/6, where the sediments have sandy-silt texture below 65 cm levels. The clays show significant temporal variations in the cores (figures 2bc–3bc). Illite and chlorite are the dominant clays in the core 31/6, but the western core (31/1) has a higher content of smectite (figures 2–3). Smectite content in core 31/1 varies between 66 and 17%, and we have observed a specific reduction in its content at 285–275, 205–195, 165–94, 50–40 cm levels (< 42–17% in these sections; $> 42\%$ in the remaining core) corresponding to the time span of 10.1–9.6 $\sim$7.3, 5.8–4.3 and 2.2–1.8 ka BP of assigned ages respectively. At these levels, illite and chlorite contents are generally high (figure 2). In core 31/6, between 65 and 200 cm levels, the illite content is drastically increased ($> 80\%$) and remains unchanged. Conspicuously, the other clays are present in trace quantities here. The core top (0–15 cm) has high smectite (range 30–51; age < 1.5 ka BP), though chlorite and illite are reduced here (figure 3).

The rates of sedimentation are different at both cores. The averaged rate of sedimentation in core 31/1 is 27.27 cm ka^{-1}. The rate of sedimentation in the central core 31/6 is highly variable. The ages
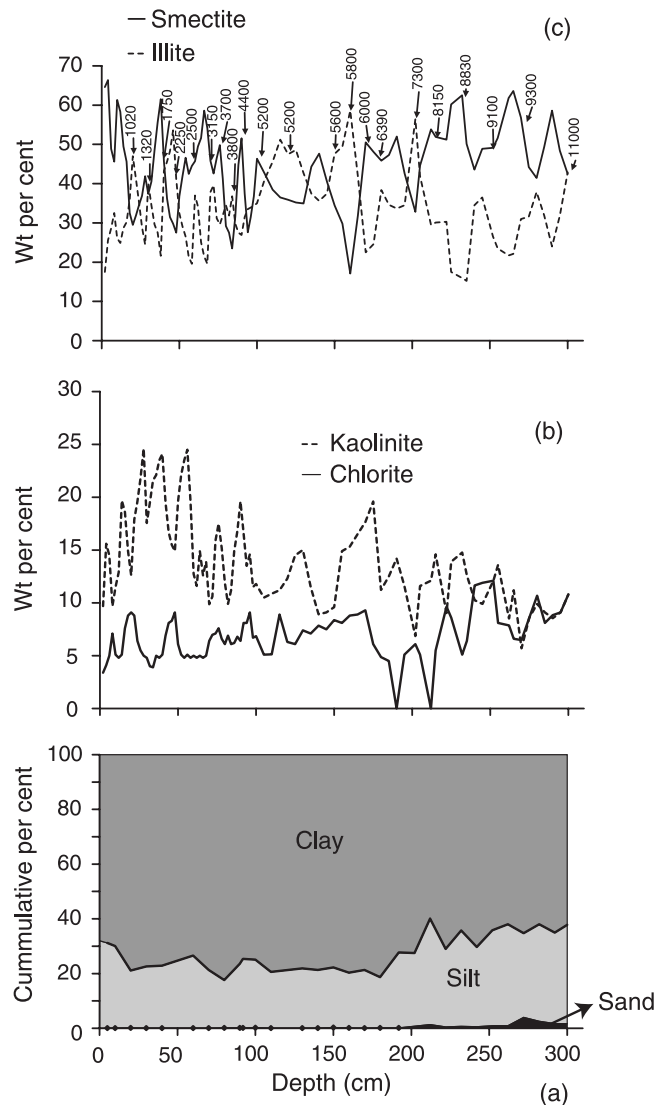

Figure 2. Temporal variations in granulometric parameters and clay minerals in core 31/1. Corrected 14C ages are shown.

are uniform or reversed between 65 and 200 cm levels. Derived from the expected decreasing trend of ^{14}C dates with depth, the rate of the sedimentation is about 11.5 cm ka^{-1} in upper 0–25 cm levels.

4. Discussions

Because the clays are the weathering product, and their production and liberation is dependent upon the geology, drainage and the prevalent climate (Weaver 1989) of a given region, the load of the Himalayan and the Indian peninsular rivers are markedly different. Konta (1985) and Subramanian (1987) have determined the clay loads of the Himalayan and the peninsular rivers respectively. These studies report illite + chlorite with minor kaolinite as dominant clays found in the load of the Himalayan rivers (Konta 1985;
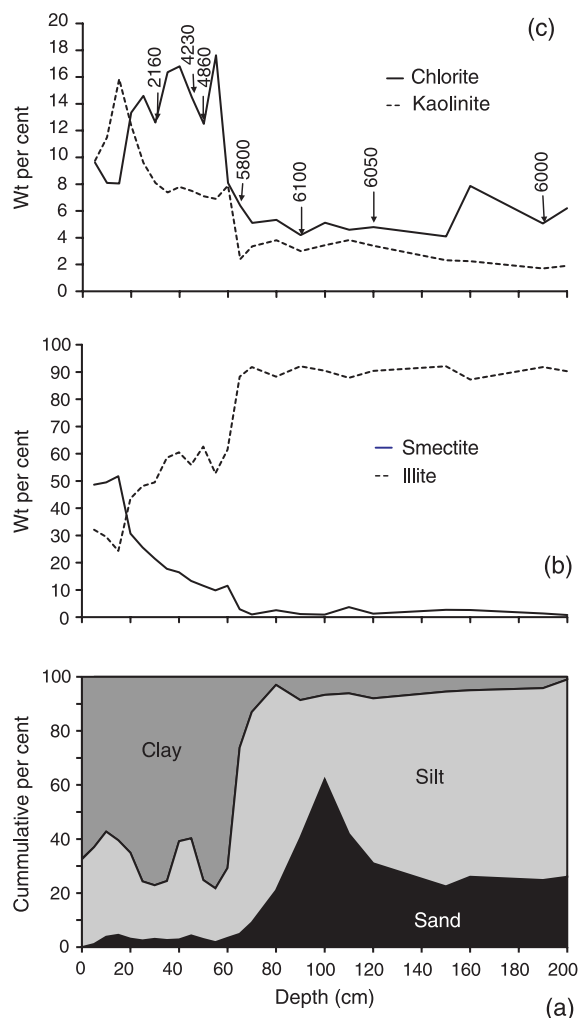
Figure 3. Same as figure 2, but for core 31/6. From higher sand, uniform ages and higher illite it is inferred that 65–200 cm levels are deposited by a turbidity event.
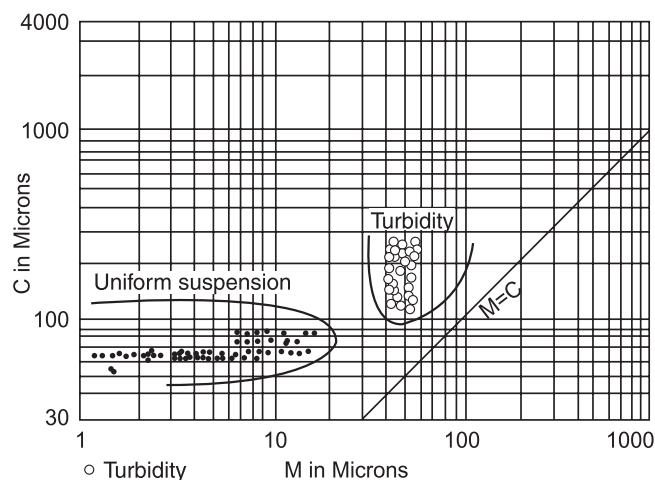

Figure 4. C/M diagram for the cores. The sediments of core 31/6 between 65 and 200 cm levels (open circles) distinctly fall in 'turbidity zone'. Closed circles for core 31/1 and 0–65 cm levels of core 31/6.

Chauhan *et al* 2004). Smectite with minor kaolinite and traces of illite are reported in the load of the G–K system (Subramanian 1987). This is expected because the peninsular rivers have a major catchment area in the Deccan Basalt, which is the main source of smectite in this region. It may therefore be inferred that smectite is contributed mostly from the Indian peninsular rivers G–K. Chlorite is conspicuous by its absence in the loads of these peninsular rivers (Subramanian 1987). Therefore, the source of smectite, illite and chlorite can be tied to the specific fluvial sources. Being found in all the rivers, kaolinite has little application to determine dispersal pathways.

Emmel and Curray (1984) have suggested mass gravity processes in the entire middle bay due to fan building activity supported by the sediment supply through the canyon of the G–B system. We have observed an increasing trend of ^{14}C dates with depth in core 31/1 (figure 2), which suggests that the core is not influenced by turbidity induced

sedimentation, and can be used to reconstruct the temporal variations in the climate induced changes in the fluvial influx at the core site. Core 31/6 from the central region, however, has reversal of the ages in the lower sections, and these levels appear to be influenced by the mass gravity processes. We have also plotted our data in C/M diagram (Passega 1964) to further evaluate the mode of deposition at each core site (figure 4). The sediments of the western core 31/1 occupy the region demarcated for 'uniform suspension'. This implies that most of the influx at this core site is through suspension, and gravity induced sedimentation is absent. However, the lower levels of the core 31/6 (central bay) conspicuously fall in the 'turbidity domain' (not deposited from water column by uniform suspension), and further corroborates an altogether different mode of deposition due to the existence of turbidity induced sedimentation in the central bay prior to 5 ka BP.

For comparison, we have evaluated the rate of sedimentation in the eastern bay from the available, published results of Chauhan *et al* (2004). The average rate of sedimentation is least here ($\sim 5\,cm\,ka^{-1}$) compared to the western or central regions. Illite, chlorite, smectite and kaolinite in the order of abundance have been reported from this site. From rather low values in the entire LGM ($<13\%$), there is an increasing trend in the abundance of smectite during the Holocene ($>25\%$; refer figure 2; Chauhan *et al* 2004). From the temporal variations in the abundance of the clay minerals in this study, it may be deduced that there are two distinct patterns during post- and pre-Holocene. Illite–chlorite dominated clay assemblage ($I + C > 60\%$; smectite $<13\%$) is observed between 65 and 100 cm levels (age 12.6–18 ka BP;
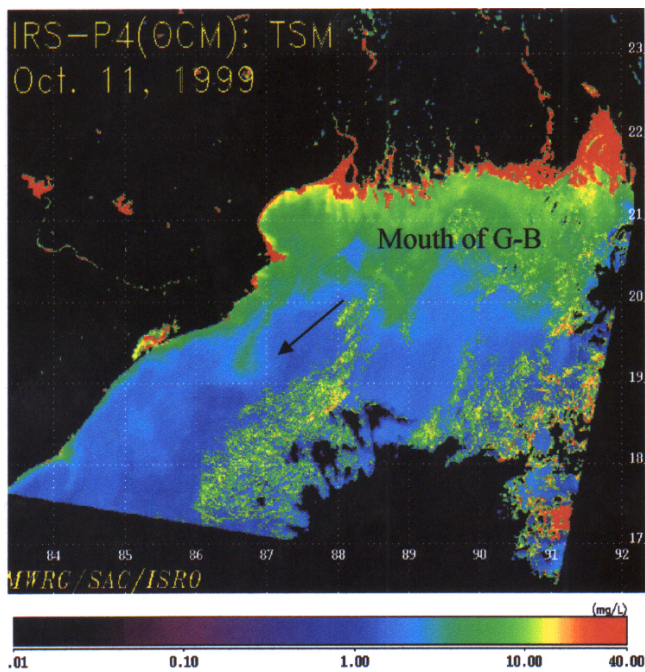
Figure 5. Geo-referenced, imagery of Indian Remote Sensing Satellite (IRS OCM P-4, 11 October, 1999) from the northern regions of the bay (modified from Chauhan *et al* 2005). Arrow shows equatorwards regional suspended matter dispersal during the NE monsoon (October–January) in the bay.

refer figure 2, Chauhan *et al* 2004), and it is inferred, therefore, that the eastern region prior to 12.5 ka BP was receiving sediments mainly from the Himalayan source. The climatic changes in the bay since last glaciations have been reconstructed in the earlier studies (Chauhan 2003; Chauhan *et al* 2004). The climate was arid between 18 and 15 ka BP, and was unstable between 15 and 12.6 ka BP with rather low intensity of the SW monsoon (Chauhan *et al* 1993, 2004; Weber *et al* 1997; Chauhan and Suneethi 2001; Kudrass *et al* 2001; Chauhan 2003). The bay witnessed intensified monsoon after 12.6 ka BP (Weber *et al* 1997; Chauhan and Suneethi 2001), accompanied with two prominent phases of freshwater influx IA and IB around 11.5 and 9.5 ka BP (Chauhan 2003; Chauhan *et al* 2004) respectively. As indicated earlier, Tiwari *et al* (2005) have reported that the SW monsoon was weak, though the NE monsoon hydrography was stronger during the LGM. This implies that the dispersal pathways were regulated by the NE monsoon hydrography prior to 12.5 ka BP, when the SW monsoon was weak. During the NE monsoon (prevalent from October through January), reported hydrography is equatorwards (Shetye *et al* 1991, 1993). We have evaluated imageries of the Indian Ocean Satellite, Ocean Color Monitor (P-4) from the northern Bay of Bengal to determine regional dispersal pathways of the suspended matter during the NE

monsoon (Chauhan *et al* 2005), which is equatorwards during October 1999 (figure 5), and further supports our thesis of southward advection of the discharge of the G–B and the K–G by the winter hydrography. Being climate dependent, it implies that the polewards hydrography of the SW monsoon was rather weak prior to 12.5 ka BP, and the clays were mostly dispersed by the equatorwards winter currents as observed in the satellite imageries.

The climate reversal after 12.5 ka BP appears to have modified the hydrography. Because during the SW monsoon hydrography is polewards, anticyclonic gyre (Shetye *et al* 1991, 1993), it will support advection and dispersal of the suspended flux of the peninsular sources into the eastern bay. There is a consistent increasing trend in the content of smectite after 12.5 ka BP ($< 13\%$ and $> 25\%$ in pre- and post-12.5 ka BP sections respectively). Higher smectite in the entire Holocene section of the eastern region ($> 25\%$; Chauhan *et al* 2004) may therefore be interpreted as an evidence of major changes in dispersal pathways of the peninsular sources due to modified hydrographic regime, i.e., an initiation of stronger across-shelf dispersal by poleward currents which appear to have sustained with minor fluctuations during the Holocene.

In the central bay (core 31/6), however, two distinct environments of deposition have been observed. Between 65 and 200 cm levels in core 31/6, the sediment texture is uniformly silty-sand. In the C/M diagrams (Passega 1964), the sediments of these levels occupy the 'turbidity'; and not the 'suspension' domain as has been the case for the sediments of core 31/1 (figure 4). These levels also have uniform or altered ^{14}C age ranging between 5.8 and 6 ka BP, and we therefore demarcate these as turbidity events in the central bay. Illite is the major clay (> 80 per cent), and its contents are more or less constant at all these levels of the core (figure 3). The uniformity in contents of all the clays, together with similar or reversed ages here, leads us to designate this entire section as one litho-unit deposited by a turbidity pulse. Due to emplacement of this turbidity, it is not possible to reconstruct the sources of the sediments in the central bay prior to the mid-Holocene. However, from the content of high illite in this entire turbid section ($> 80\%$), it may be inferred that this turbidity pulse is related to the Himalayan rivers. The signature of this turbidity pulse is not observed in other cores. The sediments of this litho-unit are dominated by the sand fraction, which cannot be transported in the suspension for long distances. Therefore, it is deduced that this episodic turbidity pulse in the middle fan regions was rather local.

The upper surfaces (0–60 cm age < 4.8 ka BP) of the core 31/6, however, have significant contents

of illite and chlorite, which are the constituents of fluvial sources of the Himalayan rivers. Smectite is also conspicuously increased in the upper section only (levels 0–15 cm, 30–51%), and the deduced mode of deposition is 'suspension' here (figure 4). Ages at these levels are also sequential without any reversal (figure 3). From the assemblage of the clays, particularly from the increasing trend of smectite (30–51%), it is inferred that this location is receiving clay flux from two distinct sources, i.e., illite and chlorite from the G–B and smectite from the peninsular sources. The occurrence of high smectite during the late Holocene (< 1.5 ka BP; content > 45%) provides further evidence of a larger influence of the peninsular rivers on the central regions of the bay, which was, hitherto, considered a depocenter of the G–B system (Emmel and Curray 1984; Kolla and Rao 1991). An average rate of sedimentation is ∼ 11 cm ka^{-1} in the central bay, which is much higher than observed in the eastern region (Chauhan *et al* 2004), even though these core sites have almost similar distance from the mouth of the G–B. The enhanced rate of sedimentation at the central bay may be attributed to the supply from the Himalayas as well as peninsular sources.

Smectite is the major clay observed in core 31/1 (range 67–21%; figure 2). Besides, illite (range 19–58%), kaolinite (range 6–24), and chlorite (traces – 8%) are observed in the order of abundance. This location lies off the mouth of the peninsular rivers G–K. A higher smectite in the core, therefore, appears to be related to proximity to the peninsular sources. From the occurrence of illite and chlorite, it is also inferred that even though the main source of terrigenous flux is from the peninsular rivers, the western bay also receives sediments of the G–B system by equatorwards dispersal. The overall rate of sedimentation in the core is ∼ 27 cm ka^{-1}, which appears to be related to:

- proximity of the core site to the peninsular rivers, and
- being the depositional site receiving sediments from multiple sources.

Being depocenter of peninsular as well as Himalayan rivers, this site is expected to archive temporal variations in the intensity of cyclonic gyre prevalent during the NE monsoon carrying the sediment of the Himalayan rivers. We have observed specific variations in the content of smectite, illite and chlorite in this core at 285–275, 205–195, 165–94, and 50–40 cm levels corresponding to a timespan of 10.1–9.6, ∼ 7.3, 5.8–4.3 and 2.2–1.8 ka BP respectively. The reduction in smectite with corresponding increase in the contents of I + C at all these levels have been observed and evaluated

with reported climate at these times to elaborate the influence of climate on dispersal pathways. There are documentations of pauses in the intensity of the SW monsoon during the Holocene at all these times (Sirocko *et al* 1993; Kudrass *et al* 2001; Agnihotri *et al* 2002; Chauhan 2003; Chauhan *et al* 2004). First of these events is specifically coeval with the 'Younger Dryas' event in the world climate model with an intensified NE monsoon regime (Kudrass *et al* 2001; Chauhan 2003). An overall reduced influx of smectite during all these known events of aridity, therefore, further supports the influence of climate on the hydrographic changes and dispersal pathways.

It may, therefore, be summarized that the sources and dispersal of the sediments in the bay have been significantly regulated by climate changes. Concurrent with the prevalent climate, winter hydrography has played a more dominant role in dispersing the sediments prior to 12.5 ka BP, when the winter monsoon hydrography was dominant.

With initiation of stronger summer monsoon regime at 12.5 ka BP, the bay has witnessed a change in the dispersal pattern, i.e., a higher magnitude of polewards, across-shelf dispersal during the entire Holocene. In the central bay, characterized by channel–levees, sedimentation is also influenced by localized, episodic turbidity pulse fed from the Himalayan sources.

Acknowledgements

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